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Model of Residence Time and Analysis of Nitrogen Removal for Two Constructed Wetlands at the Franklin Demonstration Farm in Lexington, Illinois

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MODEL OF RESIDENCE TIME AND ANALYSIS OF NITROGEN REMOVAL FOR TWO CONSTRUCTED WETLANDS AT THE FRANKLIN DEMONSTRATION FARM IN LEXINGTON, ILLINOIS

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41 Pages

Pollution from nonpoint (diffuse) agricultural runoff has grown to be a major problem facing streams and rivers. Not only are fish and other aquatic life affected, but so is the quality of drinking and recreational water resources (Brown and Froemke 2012). If current practices continue, nonpoint pollution of surface waters will increase, therefore, there is a need to apply best management practices that successfully reduce excess nutrient runoff. Studies have shown that wetlands have proven to be the most cost-effective and low maintenance method of removing nonpoint or diffused contaminate inputs (Langergraber 2005).

The biological processes and removal of nutrients in wetlands depend on the total surface area available for microbial activity in the soil and a certain period of water retention time. Knowing residence time is important as it is a measure of the total time it takes a certain quantity of water to flow through a wetland and regulates the amount of change in the water's chemistry. Since chemical processes take time, the measure of residence time is an important factor of the degree to which wetlands can change water chemistry. With the understanding that nitrogen concentrations decrease as water

residence time increases, a model of residence time will help interpret the mechanisms determining flow paths. Initially starting with a groundwater model will help to determine whether or not there is an exchange between groundwater and surface water into and out of the constructed wetlands. The main objectives of this research were to model groundwater water retention time, compare the size and gradient of two experimental wetlands, and determine the groundwater flow paths within the site and how they relate to the areas of high denitrification rates. The two constructed wetlands chosen are West and Gully (Fig. 1) located on a 250-acre farm in Lexington, Illinois. Of the two, Gully is about half the size, is lower topographically, and has a higher hydraulic head gradient.

Using the previous hydrologic data collected by Steven Van der Hoven and recent hydraulic conductivity data, a simple 3-D model was produced in GFLOW and later a more specific and localized model in MODFLOW. This model shows how groundwater moves within the subsurface, which includes the groundwater between each wetland cell (through the berms). The two wetlands can be compared as they have different dimensions, gradients, and nutrient removal rates and MODFLOW can add to these comparisons by including the water residence time and flow paths parameters. One of the key purposes of this research was to determine whether wetland design, together with the inflow and outflow rates, significantly changes the mass nitrogen (N) removal. Modeling residence time at this smaller scale aids to visualize whether larger, gentler wetlands remove N more effectively and locate the N removal pathways.

The 3-D regional-scale GFLOW model was created including both the wetlands and the subsurface tile drainage and determined that at the regional scale, groundwater

flows southwesterly toward the Mackinaw River. This overall flow influences the fate of nitrogen and the effectiveness of wetland construction parameters to a large degree when considering a regional scale rather than each wetland system by itself. MODFLOW and MODPATH demonstrate particle flow paths within the subsurface. Since the particle set flowed between each wetland cell through the man-made berms, it can be determined that whatever enters into the wetland cells can and do in fact interact with groundwater at some point in time around each cell. Both wetland systems had a southerly flow path, leading to either the Mackinaw River or Turkey Creek, which both represent the southern boundary for the model domain. The results of this research will be beneficial when considering effective wetland design, monitoring procedures, and wetland management.

KEYWORDS: Agricultural Runoff, Contaminant Transport, Groundwater, Groundwater Model, Hydrogeology, Nitrogen, Non-Point Source Pollution, Wetlands.

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TWO CONSTRUCTED WETLANDS AT THE FRANKLIN DEMONSTRATION

FARM IN LEXINGTON, ILLINOIS

EMMA SINGH BAGHEL

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E. S. B.

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CHAPTER I

INTRODUCTION

Statement of the Problem

Non-point source pollution from agricultural runoff, especially in the Midwest, has developed into a major problem to the water quality of streams and rivers (Brown and Froemke 2012). If current practices continue, nonpoint pollution of surface waters will continue to increase; therefore, there is a need to apply best management practices that reduce excess nutrient runoff as well as infiltration into the groundwater. Studies have shown that wetlands are the most cost-effective and low maintenance method of remediating watersheds under various conditions of nonpoint or diffused contaminate inputs (Langergraber 2005). Many have studied the harm done by excess nutrients and the efficiency of implementing wetlands, but there is very little information concerning the residence time of these contaminants within and surrounding the wetlands themselves (Langergraber 2007). Residence time is important because it is a measure of the time it takes a certain quantity of nutrient-rich water to flow through a wetland and the subsurface. Knowing the surface and groundwater interactions can determine how much of the nutrients at the surface have infiltrated into the subsurface and how much actually stayed within the wetland. Additionally, knowing this helps to understand how long the process takes for nutrients to flow within the subsurface and reach nearby surface features.

Literature Review

Nitrogen

Of all the life sustaining elements on earth, nitrogen is the most abundant. The bulk of this natural abundance is in a chemical form or compound that organisms do not use (Galloway et al. 2003). Compounds of nitrogen are classified as either reactive or nonreactive. Nonreactive nitrogen takes the form of N_2 and rarely reacts to materials in the environment. Reactive nitrogen compounds are often found as nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_3), and ammonium (NH_4^+) and do not accumulate naturally if microbial nitrogen fixation and denitrification processes balance each other out (Galloway et al. 2003). The actual harm of reactive nitrogen comes from how humans have changed the amount supplied to the environment. Since the development of nitrogen (N) fertilizer by Fritz Haber, a German chemist in the early 1900s, liquid ammonia synthesis (fixed nitrogen) is now considered a necessary application for crops to increase yield (Smil 2004). Today crop cultivation converts N_2 to N through biological nitrogen fixation and the combustion of fossil fuels convert atmospheric N_2 and N to reactive NO_x, creating harmful forms of nitrogen (David et al. 2010; Galloway et al. 2003).

Since World War II, the release of reactive nitrogen from anthropogenic inputs to the Mississippi River Basin has increased from 0.13 kg N ha^{-1} yr^{-1} to now over 20 kg N ha^{-1} yr^{-1} (David et al. 2010) and negatively impacts human and ecosystem health. Nitrate (NO_3^-), the most soluble and mobile form of nitrogen, reduces the oxygen levels in our blood when drinking high levels and may cause brain damage, cancer, or death (McCasland et al. 2013). As a result of these health issues and the 1972 Clean Water

Act, the EPA set a limit of 10 mg/L for nitrates as nitrogen for drinking water (EPA 2013). More importantly, the EPA set standards for identifying impaired waters within each state. In compliance with section 303(d) of the Clean Water Act, the EPA prepared a list for each state that identifies waters that do not meet the water quality standards (EPA 2012). The standards set by the Clean Water Act allow the EPA and state governments to regulate at a more strict level than simply the drinking water standards and includes the "total maximum daily load" (TMDL) program. Established in 1972, the TMDL program focused on restoring and protecting the United States' watersheds physically, chemically, and biologically (Cole 1998).

Non-Point Source Pollution

Non-point source (NPS) pollution is a widespread occurrence due to the numerous daily activities that can alter water quality. Both point and non-point sources of pollution significantly contribute to nutrient load, but NPS loadings are over five times higher and are harder to regulate (Carpenter et al. 1998). According to the U.S. National Water Quality Inventory, five of the six sources of water impairment are from NPS pollutants washed off cropland, roads, grazing lands, etc. in the form of sediment and nutrients (USEPA 2009, 2011a). Nutrients, mainly forms of nitrogen and phosphorus, become transportable through soil erosion and adsorption to sediment particles or interflow through the soil (Bhattarai et al. 2009). These inorganic nutrients can create toxic algal blooms, loss of oxygen, and loss of species (Brown and Froemke 2012). Without buffers or wetlands to stop the flow of contaminated water or filter the nutrients from the water, additional water resources may become impaired.

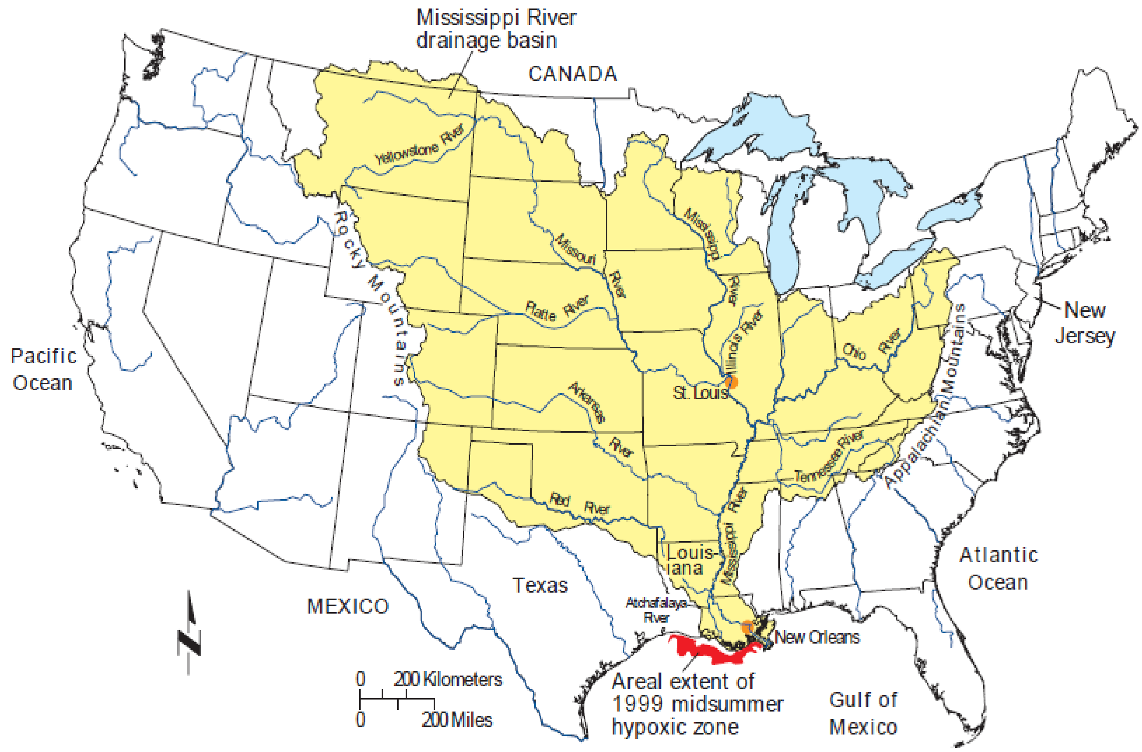


Figure 1**.** Mississippi River Basin and major tributaries. Areal extent of 1999 midsummer hypoxic zone (Goolsby and Battaglin 2000).

Tile drainage is possibly the most critical landscape aspect of crop production and NPS pollution in the Midwest (Goolsby and Battaglin 2000). Within the Mississippi River Basin (MRB), cropland accounts for 60% of the area. Between 90-95% of the cropland is tile-drained agricultural lands that serve as the dominant source of nutrient loads to the basin (Fig. 1. Goolsby and Battaglin 2000; David et al. 2010). These tiles lower the water table and transport much of the water from fields (Baker et al. 2008). The annual delivery of nitrogen from agricultural runoff, including tile drainage, from the MRB has nearly tripled since the late 1950's as this basin contains one of the major productive farming regions worldwide (Goolsby and Battaglin 2000). On average, the Mississippi River and its tributaries discharge 1.57 million metric tons of nitrogen into the Gulf of Mexico; 89% of the transported nitrogen is from nonpoint sources (Goolsby and Battaglin 2000). The hypoxic zone in the Gulf of Mexico is evidence of how nitrogen loads have tipped the balance of ecosystem stability as it causes stress or death to bottom-dwelling organisms that cannot leave the zone (Goolsby and Battaglin 2000).

Wetlands as a Solution

Constructed wetlands, like natural systems, utilize natural resources to treat impacted waters. Wetlands act as a sink by removing or sequestering nutrients and toxic contaminants (DeBusk and DeBusk 2001). They contribute to denitrification which, unlike plant uptake, is the only process that permanently reduces NO_3^- to N_2 (Batson et al. 2012). The biological processes of nutrient removal in wetlands depend on the total surface area available for anaerobic microbial activity in the soil, groundwater flowpaths, and water retention time (DeBusk and DeBusk 2001). Methods of nutrient removal may change from wetland to wetland as one wetland system may readily adsorb excess nutrients to the surface of sediments, another may absorb nutrients into vegetation and still others may strictly rely on microbial activity in the soils. Wetlands with and without vegetation have similar nutrient removal rates over a long-term basis so it is possible that vegetation does not play a big role (Mitsch et al. 2012).

Constructed wetlands may treat impaired water flowing within or above the surface of the media (DeBusk and DeBusk 2001). A natural process of permanent nitrogen removal occurs during the process of denitrification within the organic rich soil where nitrifying bacteria add oxygen to ammonia (Woltemade 2000). This process then changes the chemical structure to nitrate (NO_3^-) and finally denitrifying bacteria change it into free and harmless nitrogen by removing the oxygen in anoxic sections of the wetland (Woltemade 2000). On an annual basis wetlands are sinks for nitrates, removing an average of 85% (Phipps and Crumpton 1994). Many studies have shown that wetlands are the best method for removing nutrient loads because of their high success rates of denitrification (Fisher and Acreman 2004). Denitrification is a vital product of wetlands and in conjunction with the rate and duration of nutrient loading as well as wetland design and soil quality the ability of a wetland to utilize microbial activity and vegetation uptake can effectively complete the denitrification process (Fisher and Acreman 2004). Therefore, a properly designed wetland, together with a suitable flow pattern and a well thought out location, will most effectively improve the water output quality.

Residence Time

Another huge factor in nutrient removal is the water retention or residence time. Residence time is the average amount of time a water molecule or substance remains in a particular system, such as the surface water system or groundwater system. Residence time in wetlands can be determined by a water budget that divides the volume of water in a wetland or reservoir by either the rate of water entering the reservoir or the rate of water exiting the reservoir. In the groundwater, residence time is represented as the time a water molecule travels from a source to a sink along a groundwater flow pathway. The importance of developing monitoring procedures and models in these water bodies is to reduce as much of the contamination as possible before it flows out of the wetland and into a nearby water body, which essentially means increasing the residence time to allow maximal time for biogeochemical reactions.

Role of Groundwater

Groundwater hydraulic gradient, hydraulic conductivity, porosity, and the surrounding geology are factors that affect groundwater quality as they control surface runoff, percolation of pollution, and contamination transport in the subsurface. Groundwater receives nutrients, mainly nitrate, from overlying agricultural areas, although tile drains may prevent this from occurring in some areas with a high density of installed tiles (Dubrovsky et al. 2010). Since wetlands contain high nutrient loads, knowing whether the water is retained within the wetland or the wetland seeps into the subsurface is important for understanding where denitrification is occurring and if the wetland is effective in sequestering nitrogen. Denitrification processes in the subsurface can also be valuable for removing high nutrient loads from the water supply before they enter other down-gradient surface water bodies, such as rivers and streams (Dubrovsky et al. 2010). Nitrogen concentrations are higher in well-oxygenated water and do not depend on the source of contamination (Dubrovsky et al. 2010).

Objectives

The main objectives of this research are (1) to understand the groundwater flow dynamics and possible interaction with surface water and (2) to compare the surface water residence time with the groundwater travel times to reach the nearest natural surface features (Fig. 2). With a combination of surface and subsurface groundwater flow away from the wetlands, the residence time will be dependent on numerous variables including hydraulic conductivity, porosity, amount of recharge, volume of water, and wetland design.

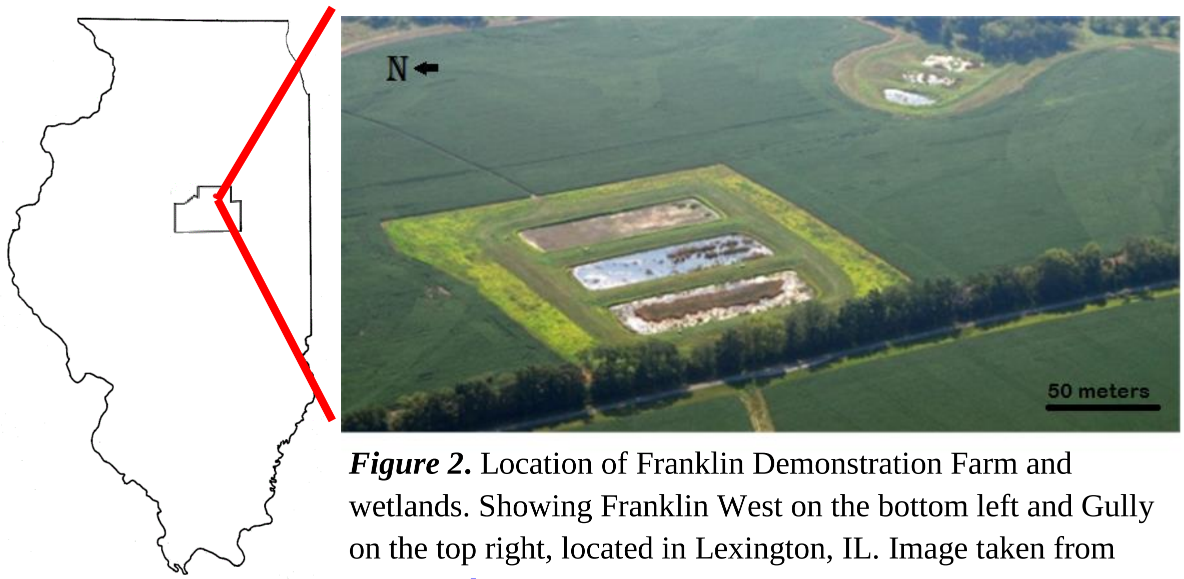


Figure 2. Location of Franklin Demonstration Farm and wetlands. Showing Franklin West on the bottom left and Gully on the top right, located in Lexington, IL. Image taken from www.ecologyactioncenter.org/mCLEANwater.

Site Description

Geology

Similar to many states in the Midwest, Illinois is overlain with glacial deposits from the Pleistocene ice ages, and these deposits constitute the exposed surficial geologic media in central Illinois. The glacial ice deposited thick sequences of diamictons, and the glacial meltwaters deposited thick beds of silt near the river valleys and much of this was blown all over the state as loess (NRCS & USDA 2013). Before settlement, the state of Illinois was mostly marshlands or wetlands, but tile drains and ditches solved the issue of the land's impractical use for agricultural (Dahl & Allord 2006). The soil consists of loess and silty clay loam subsoil with underlying glacial till (NRCS & USDA 2013). The geologic units underlying the site are part of the Wedron Group (Wisconsin Episode), which is a glacial till layer that ranges in thickness from around 3 to 30 m (Larson & Kempton 1997). The land use of the study site is classified as agricultural, and the farm was specifically made to be a demonstration and research facility (Lindenbaum et al. 2010).

Hydrology

This study is located in the Mackinaw River Watershed where farmland is tiled drained with installation about 60 cm below the surface (McLean County Regional Planning Commission 2012). Till dominates this site with permeability below a depth of 152 cm, and classified as having poor drainage, a non-hydric soil status and a medium surface runoff class (NRCS & USDA 2013). Hydrogeologic properties of the surficial deposits are found within the Wedron Group, which are not conductive. (Willman & Frye 1970). The hydraulic conductivity (K) was estimated to be around $1.16*10^{-5}$ m/sec with a porosity of 20 % which was based on similar geology consisting of gravel and broken clay (Ackerman et al. 2015). K represents the ability of geologic media to transmit groundwater and in glacial till and porosity is the void space between the sand and gravel grains. The land surface is flat, which results in poor natural drainage; however, surface streams, Turkey Creek and Mackinaw River, receive overland flow and groundwater input (NOAA 2015).

Climate

Central Illinois has a temperate climate with cold, wet winters and hot, wet summers. The temperatures vary harshly from winter to summer with a mean winter temperature of -2.5°C and an average summer temperature of 23°C. As an annual average temperature, this area circulates around 10°C (Advameg, Inc. 2015). Central Illinois receives an annual average precipitation of 1 m (Advameg, Inc. 2015).

Wetlands

In 2005, three constructed wetland systems were installed on a 250-acre property owned by The Nature Conservancy. The systems were designed to be used as a research and demonstration facility in central Illinois (Fig. 2). The wetlands systems were created to receive tile drainage from agricultural field runoff. All were lined with fine-grained clay and each cell is surrounded by an elevated, earthen berm built from the clay excavated from the wetlands. The berms were built to retain the water within the wetland system. In the upper wetlands, an inlet was installed that allows tile-drained water to enter the wetland. Each wetland has an outlet that drains directly into the next down gradient cell, with the final cell (Cell 3) discharging to a surface water body. Both of the inlets and outlets of each cell have devices installed to measure the volume and velocity of flow. There is one inlet and one outlet for each cell, the primary, secondary, and tertiary cell. This study focuses on the West wetland system and the Gully wetland system. The elevation of the land surface for the site is an average of 220 meters above sea level and the land surface has an average gradient of 12 meters over a distance of 1,164 meters, representing a relatively flat land surface. West and Gully are two wetland complexes that vary by dimensions, hydraulic and topographic gradients, flow rates, surface water residence times, and nutrient removal rates. Both are included in a groundwater flow model produced in MODFLOW. The systems were chosen because

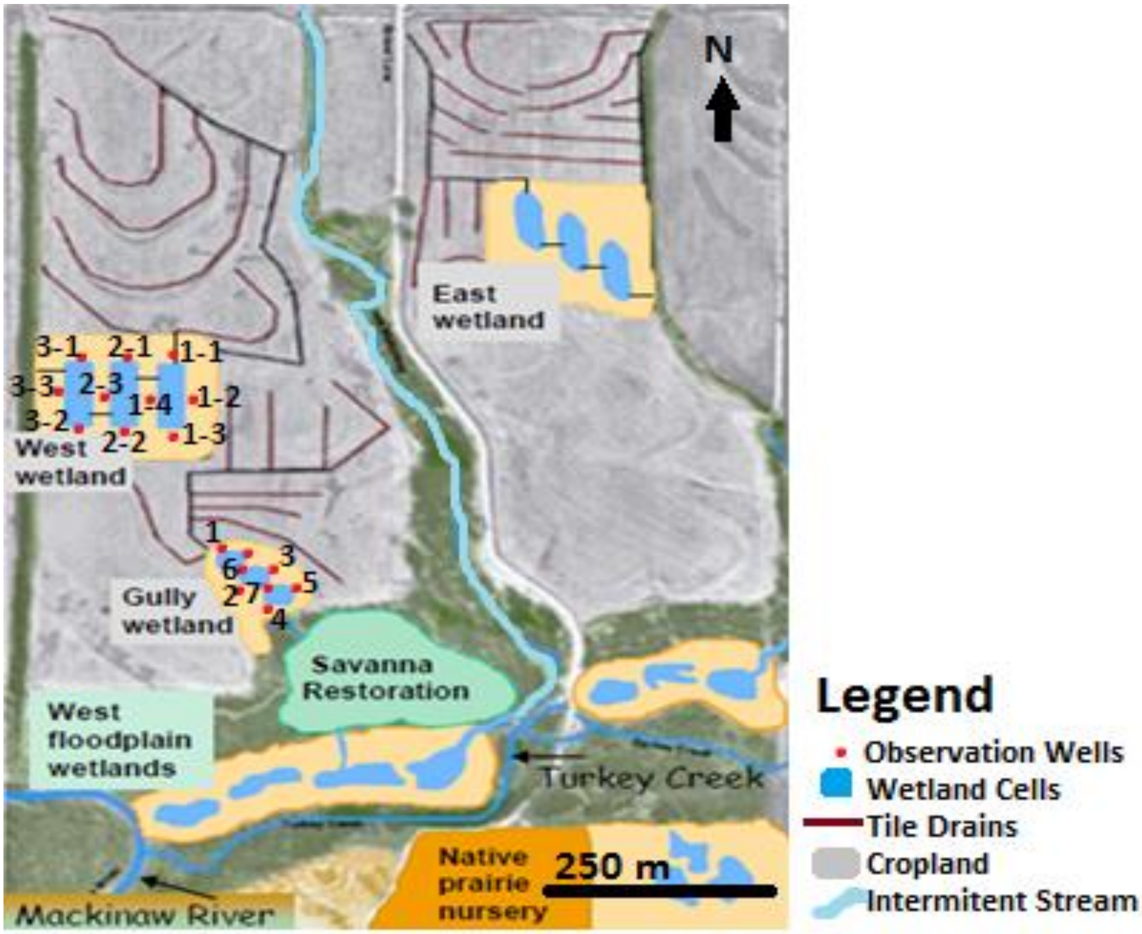


Figure 3. Map of site specific locations of surface and near-surface features. The National Conservancy Demonstration Farm image taken from Lindenbaum et al. 2010 showing the locations of the tile drains, wetland cells and observation wells.

they have monitoring equipment installed and several years of ample well data. Each system, West and Gully, account for 9% of the tiled drained area the drain into the respective wetland. Since each system drains different areas, the total areas of the cells differ between the complexes (Fig. 3) (Lindenbaum et al. 2010).

Table 1. *Comparison of Two Constructed Wetlands*

	West	**Gully**
Total Area (3 cells)	130 m X 85 m	85 m X 25 m
General Land Surface Gradient	0.6	2.1
Orientation to GW flowpaths	Perpendicular	Parallel
***Ave. Total Residence Time**	1.41 day (33.772 hr)	0.011 day (0.255 hr)
***Denitrification Rate**	10.36 mg N/kg/hr	84.15 mg N/kg/hr
***Nitrogen Removal**	60%	39%

*Values taken from Lindenbaum et al. 2010.

In addition, automatic samplers located within the cells collect water samples that were later analyzed for dissolved nitrogen (nitrate and ammonium) concentrations. Soon after the wetlands were created, several monitoring wells were installed in 7.5 cm boreholes both within and around each cell with the screen depth set to intersect the water table. West has a total of 10 observation wells, one in the center of each of the two berms separating the three cells and the others surrounding the cells on each side. Gully has eight wells surrounding the three wetland cells. These wetlands have been successful over the years for decreasing the dissolved nitrogen load. According to the preliminary monitoring data from the 3-year study (2007-2009), West showed an average cumulative nitrogen removal of 60% and Gully exhibited a 39% removal (Lindenbaum et al. 2010).

The two experimental wetland systems adequately remove nitrogen from the area, but are different systems altogether due to their differences in design and orientation (Table 1). West was designed to have surface water flow east to west, perpendicular of the north to south direction of groundwater flow. Gully was designed to have surface water flow northwest to southeast, which lies almost parallel to the groundwater flow. Gully on the other hand has wetland cells that encourage faster surficial flow from north to south. West is the larger of the two systems in dimensions and has a gentler water flow gradient, thereby supporting a longer residence time, but the system as a whole has more N released in the outlet pipe than that of Gully. Gully has a steeper land surface and hydraulic gradient in conjunction with a smaller surface area. It appears that the Gully system retains more water within the wetland cells and yet the wetland's residence time is faster (about 2 orders of magnitude) than West, which introduces the possibility of groundwater influences on water and nutrient transport from the wetland.

CHAPTER II

METHODS

Data Collection

Slug Test and Hydraulic Conductivity

Slug tests were performed to obtain hydraulic conductivity (K) of the porous media at each observation well for the two wetland systems. Eight out of the 18 wells were used for the slug test. Only a falling head slug test was completed at each well for West and Gully rather than both a rising and falling head test. An In-Situ, Rugged Water Level TAPE was used to provide water level measurements within the wells by sounding an alarm whenever the meter comes in contact with water. The data were reduced method using the Hvorslev Slug Test Method (Hvorslev 1951; Equation 1). This mathematical solution yields values of K for over-damped tests in unconfined aquifers and omits storativity. Incorporating well construction, this method uses a plot of h/h_0 against time on a semi-log plot to determine T at $h/h_0 = 0.37$ where h = change in

$$K = \frac{{r_w}^2 * \ln\left(\frac{L_e}{r_w}\right)}{2 * L_e * T} \tag{1}$$

water level and h_0 = initial height of water. Using Equation 1, hydraulic conductivity (K) was found in m/sec, where r_w is the radius of the well in m, L_e is the length of the screened (perforated) section of the well in m and T is the basic time lag in seconds. This solution assumes steady-state flow, homogeneous, uniform thickness of the geologic media, and that the aquifer has an infinite areal extent (Hvorslev 1951).

Groundwater Modeling

Regional Model

A large-scale regional flow model was established using GFLOW (Haitjema 2007) to determine the groundwater boundary conditions required for a larger-scale local model. The model extent is much larger than the local model, Franklin Demonstration Farm itself, so as to incorporate major regional hydrologic factors. GFLOW required minimal information and provides a quick steady-state flow model. The base map chosen was a binary bit map (bbm) quadrangle number five from the Fairbury quadrangle (epa.gov). The 2-D model focused on the x- and y-dimensions since the z-dimension was effectively insignificant when assumed to be an infinite thickness. The base elevation was estimated at 100 m with an aquifer thickness of 100 m, a K of $1.16*10^{-5}$ m/sec (taken from a similar area, but more representative of a sandy or disturbed till), and a porosity of 20% (Ackerman et al. 2015). There was an option to use inhomogeneity elements, but as it did not alter the model when keeping the default properties, it was unnecessary to include more details. Using the line-sink function, the four boundary conditions were drawn manually to match the centerline of the river or streams (Fig. 4).

The starting and ending head values were taken from data provided by Google Earth (Google Inc. 2015) and treated as “Head-Specified” and “far-field” values because these surface bodies could not be seen while standing by either wetland. A conceptual model was developed using geologic and hydrogeologic data. Regionally, the Mackinaw River to the southwest and Turkey Creek to the southeast can be classified as Dirichlet (constant head) boundaries as they are both perennial streams fed by baseflow.

The western boundary was Buck Creek, a tributary to the Mackinaw. Since the natural hydrogeologic boundary to the north was an intermittent tributary to Turkey Creek (Fig. 4), the DEM (digital elevation model) in ArcGIS (ESRI 2014) confirmed that the northern portion of this regional site served as a high point topographically and acted as a groundwater divide thereby forcing groundwater flow toward the southern portion. The eastern boundary is Turkey Creek.

Local Groundwater Flow Model

A local 3-D groundwater flow model was created using MODFLOW (Harbaugh & McDonald 1996). The boundary conditions were different than the regional model with an alteration of the northern boundary set to the 217 m potentiometric contour line simulated in GFLOW, making it a constant head boundary (Fig. 4 & 5). The west and east boundary conditions were also established to correspond with groundwater flowpaths delineated from the regional model results. The flowpaths can serve as no-flow boundaries, specified flow boundaries with a flux (derivation of head) of zero (Fig. 4). The lower boundary of the domain has some vertical flow, but assuming that the geologic subsurface just below the site is till, with limited vertical hydraulic conductivity, horizontal flow is magnitudes greater than the vertical flow. Thus, the lower boundary is represented as a no-flow boundary. The top boundary collects recharge and completes the system as an effective 3-D model. Elevations of topography and surface water levels were measured by looking at elevation values in Google Earth.

All four layers were considered convertible or unconfined. The geology of the site was generalized as glacial till and overall homogeneous and anisotropic to simplify the model (Table 2). MODFLOW gave an initial vertical anisotropy of 3 and a horizontal anisotropy of 1, which were not altered for this model. Grid cell size ranged from 40 m X 40 m along the periphery of the modeled area and 10 m X 10 m near the wetland complexes where higher resolution grids encompass the wetlands. The x and y dimensions are not all the same since the grid cells containing the wetlands needed smaller grid spacing for greater sensitivity and therefore more grid lines were placed (Fig. 5). Four layers were determined to be sufficient as the depth necessary reached from the top of the surface elevation at the highest point of the model area to the bottom of the Mackinaw River and Turkey Creek. Each layer represents 5 meters of thickness with the tiles and wells within the topmost layer. With four total layers, the total model thickness is 20 meters. The surface topography was properly represented within the topmost layer.

Table 2. *Parameters Used In The 3-D MODFLOW Model.*

Parameters	**Value**
Tile Drain Conductance	(0.2826 m^3*1.616 m/day)/**L** m^2/day/m
Top Elevation	227.0 m
Bottom Elevation	198.0 m
Horizontal Hydraulic Conductivity (K_h)	1.16*10^{-5} m/sec
Vertical K/Vertical Anisotropy (K_h/K_v)	3.0
Horizontal anisotropy	1.0
Recharge Rate	0.0027 m/day

NOTE: Conductance varies each stretch of tile changing with L, length of drain.

Various parameters were considered for completing the model and are shown in Table 2. The locations of the observation wells were imported from UTM coordinates gathered with a GPS unit at the site. The observed heads for the wells recorded, but the locations of the tile drains were established by examining Figure 3 (Table 3).

Table 3. *Observed Head Values For Wells.*

Well Name	Observed Head (m)	Well Name	Observed Head (m)
WW1-1	221.68	**GMW1**	220.22
WW1-2	221.52	**GMW2**	219.45
WW1-3	221.2	**GMW3**	219.65
WW1-4	221.35	**GMW4**	218.65
WW2-1	221.48	**GMW5**	218.9
WW2-2	221.04	**GMW6**	220.0
WW2-3	221.12	**GMW7**	219.2
WW3-1	221.27		
WW3-2	220.9		
WW3-3	221.02		

NOTE: Observation well names for the West wetland begin with WW and are followed by a numerical sequence with the first number representing the cell number (1, 2, or 3) and the second number representing the well number around each cell. Gully monitoring wells were named GMW followed by a number between 1 and 7.

The tile drains were positioned within layer 1 as they were all assumed to be buried at a depth between 0.67 to 1.67 meters as a general rule. Conductance for the tile drains was calculated by using Equation (2) where K was the hydraulic conductivity; A is the gross cross-sectional area of a cylinder and L being the flow length of the tile,

$$Conductivity = \frac{KA}{L} \qquad (2)$$

which varies between each tile segment. Flow rates in and out from the Slug Test showed an overall cumulative GeoMean K of ($4.442*10^{-6}$ m/sec*86400 sec/day =)

0.3838 m/day for both wetlands, which was used instead of the literature value provided by Ackerman et al. (2015) and used in the previous GFLOW model. An A of 0.2826 m^2 (3.14*(0.3 m)^2) divided by each L, in meters, gave a different conductivity for each tile drain section with varying lengths of pipe (using a radius of 0.3; Table 2). For simplicity, the clay liner for each of the wetland cells was not included in this version of the 3D model, which should be kept in mind when considering the results of the model showing connectivity between the surface and groundwater. In terms of K, the clay liner would have been 2 to 3 order of magnitude smaller than the compacted, but disturbed and reworked till, ~10^{-9} m/s, used to create the berms surrounding the wetlands.

PEST & MODPATH

PEST (Doherty et al. 1994) is a program, when coupled with MODFLOW, inverse models hydrologic parameters using known head values. It can iteratively adjust a set of parameters and repeatedly launch a model until the computed output matches the in-field observed values. PEST contains a nonlinear predictive analyzer that guarantees the model parameters used by the calibration process are respected. A list of parameters that were adjusted included hydraulic conductivity (K_h), recharge, and porosity (Table 5). This was either done by either increasing or decreasing the value, with a default weight of 1.0 until the error was as small as possible and the observed vs. calibrated graph approached a 1:1 ratio.

MODPATH (Pollock 1994), a forward modeling particle tracking simulator, was run and showed the fate of particles, starting from within the wetland. Before the model run, one particle was placed in the surface (layer one) of each grid cell that represented the three wetland cells of both West and Gully. West has a total of 30 grid cells in the primary and secondary cells and 40 grid cells in the tertiary cell giving a total of 100 particles for the complex. Gully does not have grid-like divisions and rather than rectangular cells, they are more hexagonal and rotated, making it difficult to get a perfect grid cell count. An estimated 11 particles were placed in the primary cell, 12 in the secondary and 10 within the tertiary giving a total of 33 particles placed in layer two. Flow lines were created showing the path, destination, and time it took each particle to travel from those points within each grid cell.

CHAPTER III

RESULTS

Slug Test Outcomes and K Determination

WW1-1, WW1-2, WW1-3, WW2-1, WW2-2, and WW3-1 were either too muddy or the water level restabilized too fast for an accurate or usable reading (Fig. 3).

Table 4. *Falling Head K Values (m/day) For Each Observation Well.*

WW 1-4	0.51	GMW1	0.37
WW 2-3	0.52	GMW3	0.54
WW 3-2	0.32	GMW5	0.36
WW 3-3	0.35	GMW7	0.20

Geometric Mean WEST: 0.416 m/day & GULLY: 0.353 m/day.

The well casing for WW3-1 on the other hand was unavailable since it was not found probably due to a tractor mowing over it or was damaged by some other means. The wells for Gully that a slug test was not accomplished for were GMW2, GMW4, and GMW6. The first two were either too fast for a usable reading or no water table could be reached by the slug and tape measure. GMW6 is located within the berm separating the secondary cell from the tertiary and the well casing was found completely removed and could not be tested. The K values derived from the slug tests and Hvorslev's equation

(Table 4), found that West had a geometric mean of 0.416 m/day for the four wells and 0.353 m/day for the four wells for Gully (Bouwer & Rice 1976). A K value of 0.38 m/day was used for the overall site.

Modeling Results

The calibration completed with PEST gave a total sum of the weighted residuals as less than zero after the K, recharge, and porosity values were slightly altered to produce the best possible model outcome. The slug test provided a Geometric K value

Table 5. *All Parameters Used In MODFLOW That Were Modified With PEST.*

Parameters	**Original Value**	**Modified with PEST**
Recharge	0.002739 m/day	*0.0002 m/day*
Horizontal K	0.384 m/day	*0.385 m/day*
Porosity	20-30%	*15%*

0.384 m/day overall which changed the Horizontal K value, which is in line with the value obtained using PEST (Table 4 & Table 5). Recharge was changed to 0.0002 m/day, a more accurate representation of annual rainfall and porosity was set at 15% (Table 5). In order to find the best fit model PEST ran the model in MODFLOW during each optimization iteration and completed one run for each adjustable parameter as it calculated the optimal parameter value. The tile drain conductance values were also altered but saw no effect on the model results.

The initial regional model in GFLOW simulated a regional water-table surface of the site (Fig. 4). The solution provided general groundwater flowpaths toward the south where the Mackinaw River, the main surface water feature in the area, is located (Fig. 4; with blue arrows pointing south to represent the groundwater flowpaths). The regional flow paths show that groundwater flows toward these surface features that are down gradient from the wetlands and of a lower hydraulic head. Therefore the regional model helped create the boundary conditions used for the localized model for better resolution. Inside the local model area, outlined in red on Figure 4, the flow paths appear to flow southerly.

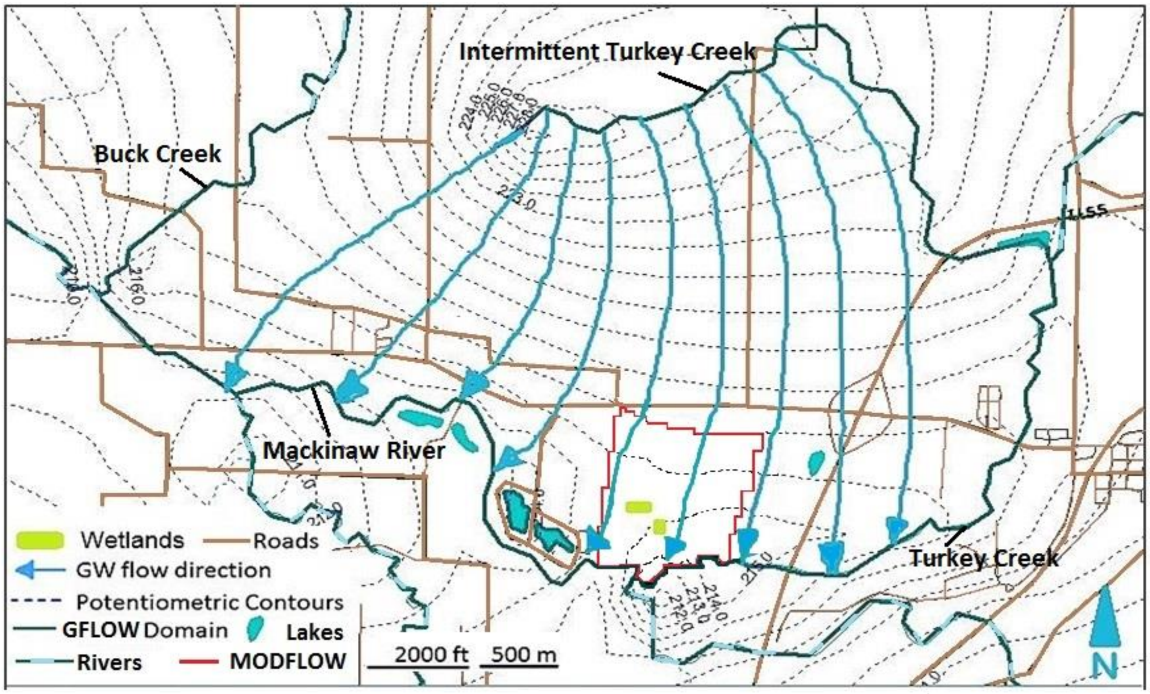


Figure 4. GFLOW and MODFLOW domains and general groundwater flow. Domain line locations outlined in GFLOW with dotted potentiometric contour lines as well as the MODFLOW domain outlined in red. The GFLOW domain symbology is similar to that of the Rivers symbology because the boundaries are rivers. The MODFLOW boundaries consist of rivers (S), a potentiometric contour (N), and two flow paths shown by arrows (E & W boundaries). Map shown in 1 m contour intervals and a max contour of 228 m.

MODFLOW created another groundwater flow simulation showing a similar south-southwesterly hydraulic gradient toward the Mackinaw River. A cross section was created to show the hydraulic gradient with contour lines showing a little more variation from vertical nearer to the larger surface features such as a river or stream and that the colors are a range, not just one value (Fig. 5 & 6). Of the four layers in the z-dimension, layer one had a range of hydraulic head from 222.8-225.6 m, layer two ranged from

220.0 – 222.8 m, layer three from 215.8 – 220.0 m and layer four from 214.4 – 215.8 m (Fig. 5). The location of this cross section was chosen because it had a wetland cell,

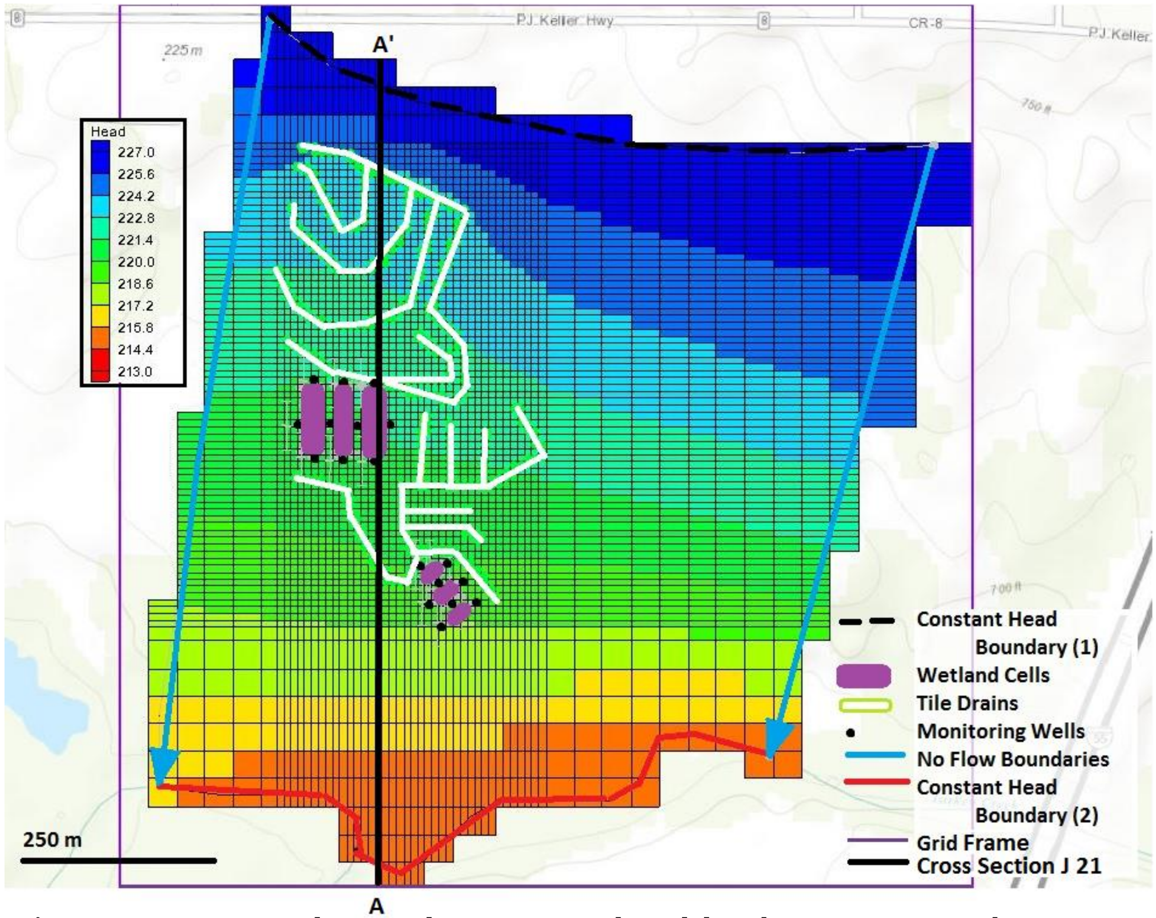


Figure 5. MODFLOW layer 2 plan view. Local model with a cross section shown in black from A-A' (Fig. 6). The hydraulic heads were depicted by a color scheme with contour lines showing the wetlands located within the medium ranges of head with a contour interval of 1.4 m (Fig. 4).

some tiles, and a good representation of change in gradient. The model run gave a flow budget for each wetland cell (Table 6). The amount of water entering the subsurface from the wetland systems can be explained by Table 6 where the *Cell to GW* is the flow of wetland water into the groundwater and *GW to Cell* is water flowing from the groundwater into the surface water cells. This flow represents groundwater where the primary cell of West has a flow from the wetland system into groundwater.

With a groundwater flow of 3.23 m^3/day into the wetland and a flow of -3.11 m^3/day out of the wetland into the groundwater, this primary cell is considered a

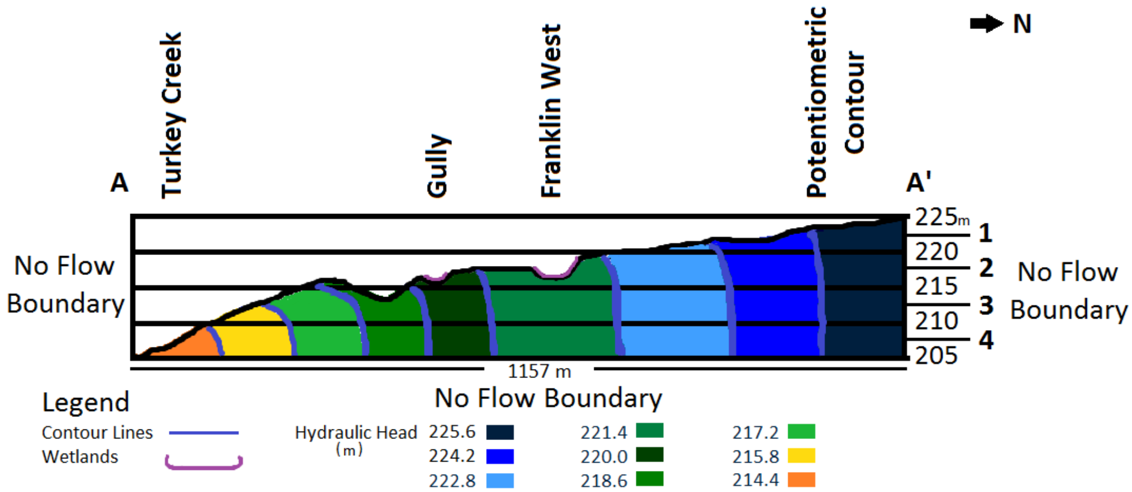


Figure 6. Cross sectional view of model in reference to Figure 5. Column J, 21 side view of local model with a vertical exaggeration of 11 with 1 inch = 25 m in the vertical dimension and 275 m in the horizontal dimension (layers 1-4).

Table 6. *Interaction Between The Three Wetland Cells And The Groundwater.*

Wetland Cells	GW to Cell (m^3/d)	Cell to GW (m^3/d)	Net Flow (m^3/d)*
West Cell 1	3.23	-3.11	0.12
West Cell 2	4.78	-1.26	3.52
West Cell 3	14.09	0.0	14.09
Gully Cell 1	0.02	-0.19	-0.17
Gully Cell 2	3.89	-2.28	1.61
Gully Cell 3	12.43	0.0	12.43

Note: West cells found in Grid Layer 1 and Gully cells in Grid Layer 2 (Total Zone Flow: Flow from cell to groundwater as recharge (Cell to GW) and flow from groundwater to cell as discharge (GW to Cell) produced by MODFLOW).

* A positive value represents a net flux into the cell (groundwater discharge); a negative value represents a net flux into the groundwater (groundwater recharge).

discharge zone for groundwater (Table 6). The secondary and tertiary cells of West show more water flows from the groundwater into the surface water; therefore, making these zones of discharge. As for the Gully wetland system, cell 1 serves as recharge zone for groundwater and the two other cells are discharge zones for the groundwater (Table 6). The wetlands may act as one source of recharge for the groundwater during dry seasons, but in this case the wetlands are not a good source of recharge.

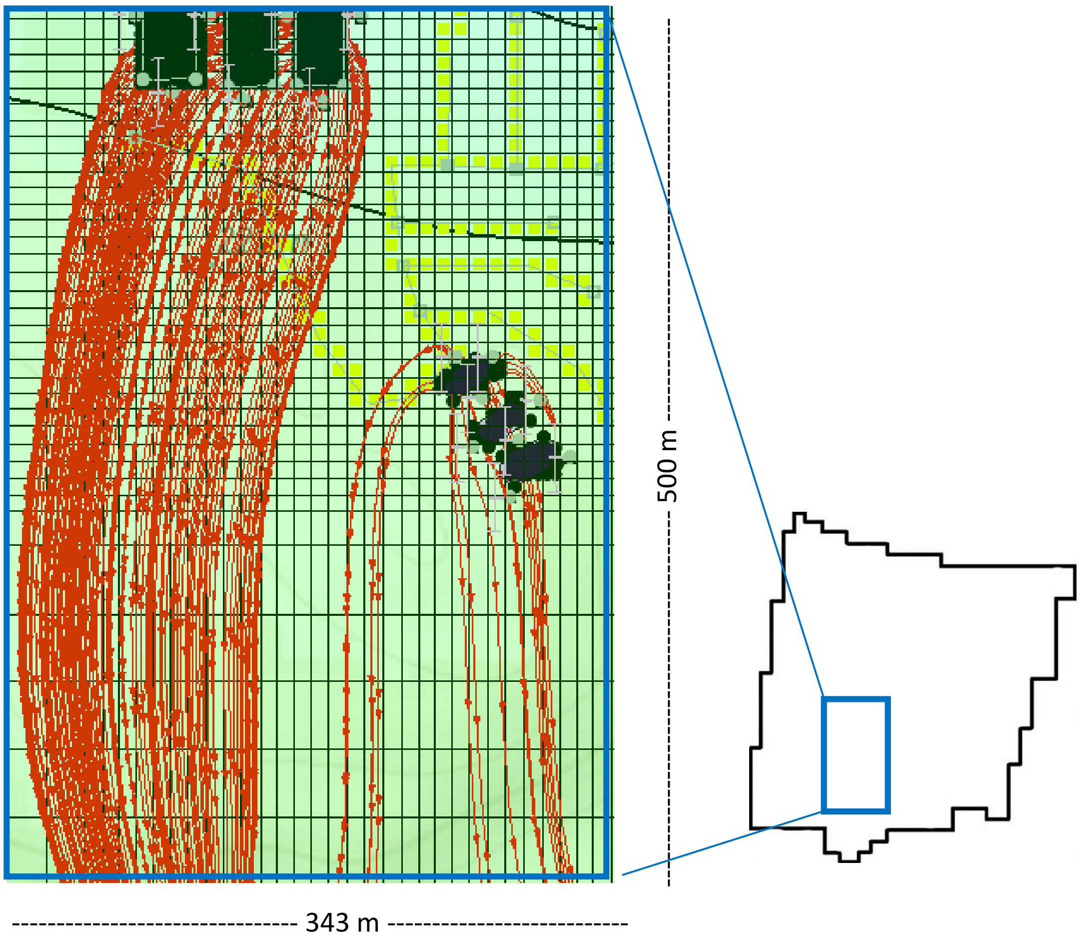
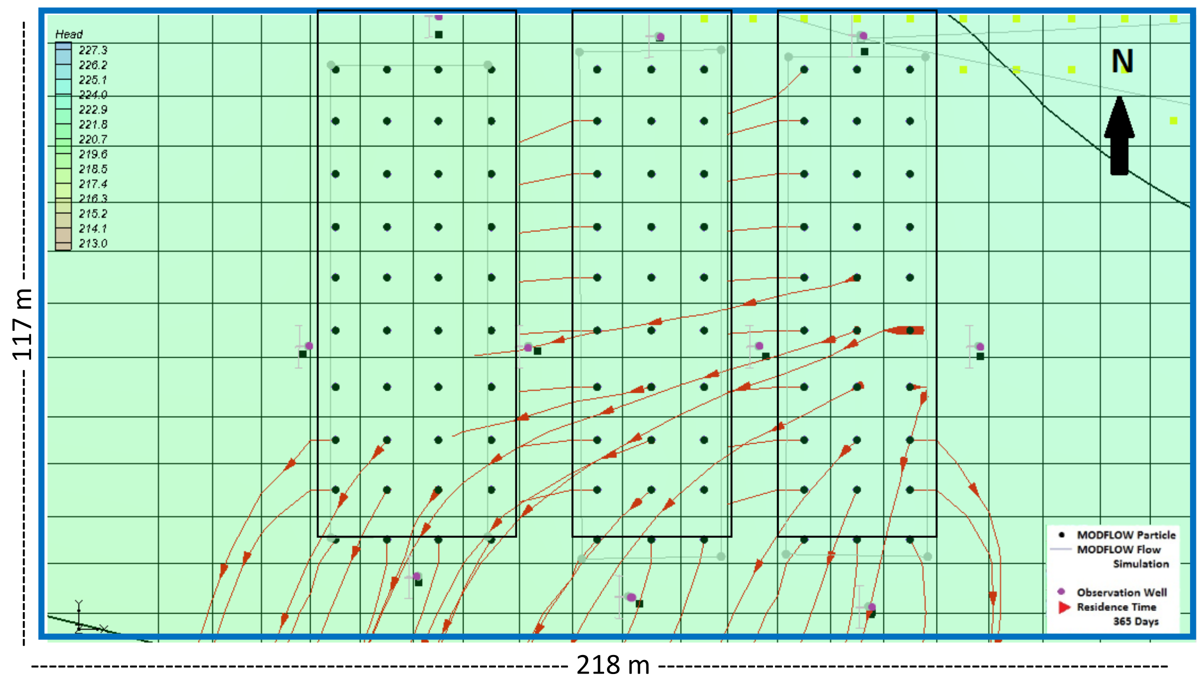


Figure 7. Particle Tracking Simulation of both wetlands. MODPATH showing no connectivity in the subsurface flow paths between the two wetlands.

The inflow vs. the outflow results of Table 6 show that not all of the water that enters the primary cell of a wetland leaves through the designed outlet cell at the surface. Rather, a portion of water found within each wetland leaches into the subsurface and becomes groundwater shown by the *GW to Cell* showing groundwater discharging into the surface cells (wetland system).

MODPATH simulated particle transport to the south (Fig. 7) with the parameters calibrated and the values for hydraulic conductivity and recharge only slightly altered. The simulated results show that groundwater does not flow from one wetland to the other, but had a southern gradient directly flowing toward the Mackinaw River and Turkey Creek.



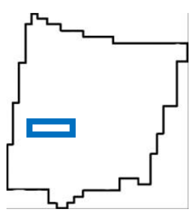
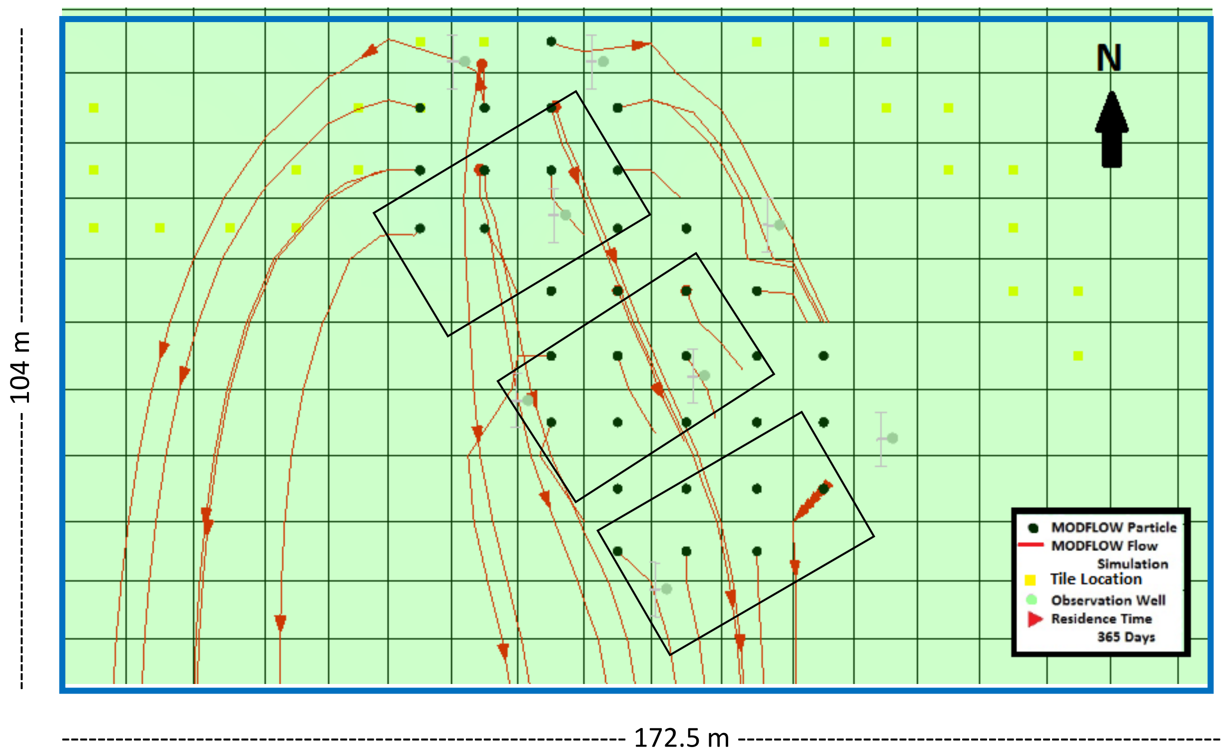


Figure 8. Franklin West MODPATH Particle Tracking Simulation. Simulation with one particle within each grid cell of all three wetland cell complexes so as to not be too cluttered and busy.

The red arrows represent a particle's location after one year when considering the gradient and hydraulic conductivity (Fig. 7-9). MODPATH generated particle travel times of 365 days for water infiltrating from the wetland and detected in the nearby observation wells (Fig. 8 & 9). The West complex has most of the particles traveling from the southern portion of each cell toward a southwesterly direction. MODPATH results shows particles traveling from West at an average of 36 m in a year ($9.85*10^{-2}$ m/day), with the arrows leaving different sections of the wetland cells at a point. The moment a red line appears from any dot inside the wetland cell, shows when the wetland water has entered the groundwater and thus travels within the subsurface (Fig. 8). Gully's primary cell splits particle directions between traveling east or west, but all cells eventually transfer the particles southerly (Fig. 9). Gully has a larger range of annual travel distances with the shorter distances near the wetland cells at distances around 50 m



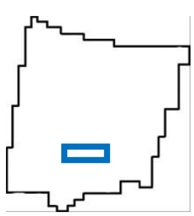


Figure 9. Gully MODPATH Particle Tracking Simulation. A maximum of five and a minimum of four particles within each grid cell of all three wetland cell complexes. These were determined to help add more particle tracking since only one particle in each cell was not sufficient to analyze.

per year (0.14 m/day) and the distances furthest south averaging to 80 m per year (0.22 m/day). MODPATH shows the travel time just north of the primary cell of Gully is an average travel time of 10 m/yr ($2.7*10^{-2}$ m/day) flowing generally west. Using the particle tracking method, it would take an average of 10 years for particles or nutrients to travel from West to reach the Mackinaw River and close to six years for particles placed in Gully to reach Turkey Creek or the confluence of the creek and the Mackinaw River. Remembering that a clay liner was not incorporated into the model, MODPATH shows the exchange of water flow between the surface and subsurface relatively easily.

CHAPTER IV

DISCUSSION

The underlying foundation was that groundwater flow paths influence the fate and chemistry of water within and around each wetland at the site. This was found to be true with the particle tracking simulation showing particles, aka: water molecules, leaving the wetlands and entering the subsurface even before passing through the surface outlet (Fig. 9 & 10). The inlets and outlets were designed to force the surface water flow through a particular flow path designed to remove the most nutrients by creating a longer residence time. The model results show that a portion of the surface water does not make it through the designed surface pathways. With a net influx volume of 17.73 m^3/day flowing into the West Complex and 13.87 m^3/day flowing into the Gully complex, more water is actually recharging the wetland systems from the groundwater (Tables 6). This implies that there is a potential for dilution, which would skew any previous denitrification calculations because they assume that the volume of water is sourced from the tile drainage themselves and this turns out to not be the case.

The amount of water exchange would most definitely be less if the clay liner was included in the model, but not including this can help to show which direction flow would most likely travel even with a liner (leaky or not). Therefore, the amount of nutrient-rich wetland water becomes more diluted as the groundwater enters and is considerably beneficial to decreasing the overall amount of excessive nutrients before they exit the wetland system (Ackerman et al. 2015). The dilution, or further treatment, of the contaminated wetland water by the discharge of groundwater into the system has been seen in other situations, such as a former case in Sacramento where the additional groundwater helped minimize contamination risks to acceptable levels once it reached a large river (Nolte & Associates 1997).

The MODPATH model showed that surface water in West sunk into the subsurface just below each wetland cell and entered the groundwater between the cells through the berms. Therefore some of the water escaped to the groundwater before it completed its winding path through the wetland and exited each cell through the desired outlet pipe (Fig. 8). The grid cells with no red flow lines simply mean that none of the surface water leached into the subsurface to become groundwater and the particles placed in those cells stayed within the surface water. Therefore, the wetland was indeed keeping a portion of the water within the system and assumedly removed nutrients in the surface water. Water that enters the subsurface are subjected to subsurface processes that mitigate nitrate. Ackerman et al. (2015) reported a significant reduction in nitrate concentration in water after infiltrating into the subsurface. Thus, the nitrate is removed during flow within the subsurface, and the exchange provides a net loss of nitrate for the system. Of the simulated particles in West that percolated into the groundwater, many were located in the southern section of each wetland cell and tended to flow either southwest underneath the wetland cells or directly south (Fig. 8).

According to the flow budget, both wetlands act as discharge zones for groundwater with only Gully’s primary cell serving as a recharge zone for groundwater. Figures 11 & 12 provide a snapshot of the flow dynamics for the exchanges. Although in some places it looks like no water is being transferred from the wetland into the groundwater, exchange does occur (faces of the grid cells). Overall, the little amount of recharge into the groundwater from the West wetland is greater than that of

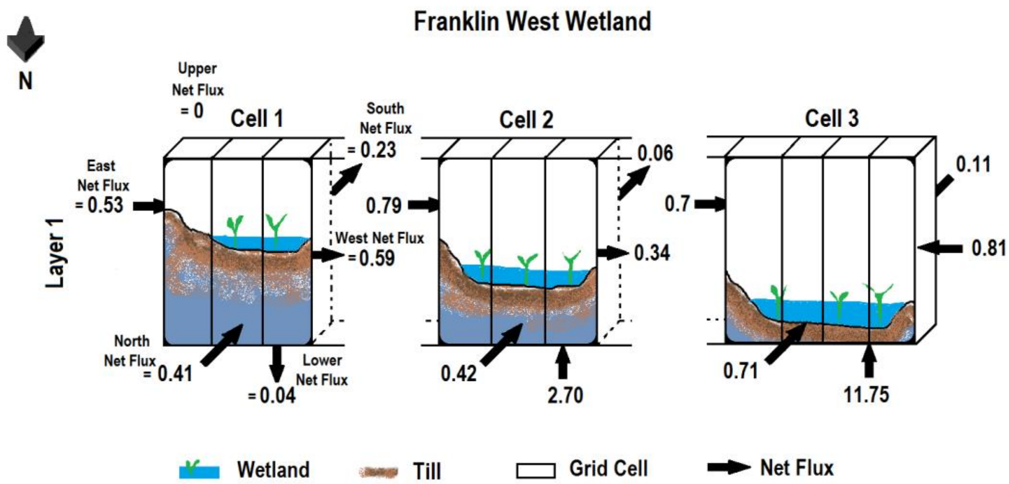


Figure 10. Franklin West net flow conceptual 3D flow model. Cross section facing toward a southerly view with Cell to Cell (zone) flow from “Right Face” to “Left Face” (East to West).

Gully and both recharge the subsurface flow most heavily in the tertiary cell. In both primary cells, there is a more even amount of recharge and discharge between the surface and subsurface water bodies.

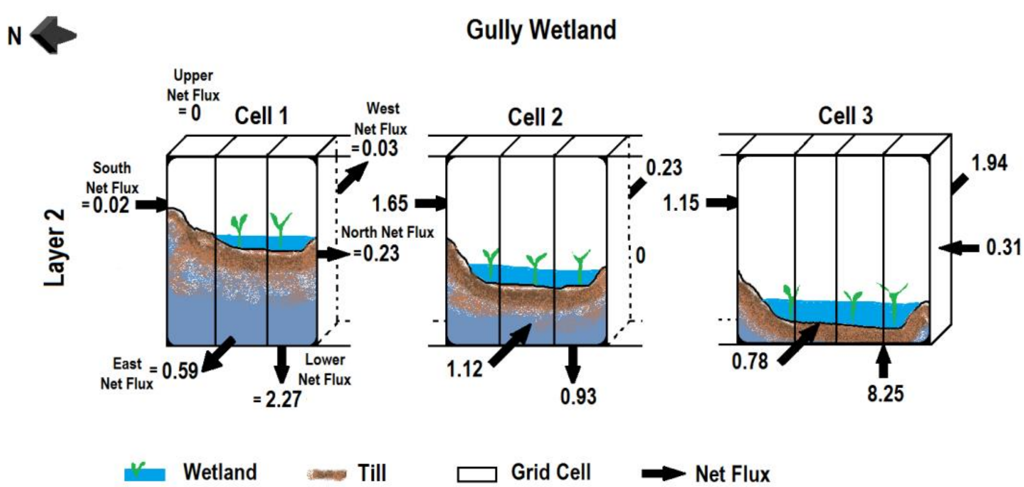


Figure 11. Gully net flow conceptual 3D flow model. Cell to Cell (zone) flow from “Back Face” to “Front Face” facing East.

The orientation of the West system was designed to move surface water flow in a westerly direction to an intermittent ditch and was perpendicular to overall groundwater flow. This position and design may have also played a part in slowing residence times within the surface water. Gully on the other hand had an almost parallel flow design for surface water when compared to the groundwater flow paths. What is unique about the Gully wetland system is the higher volume of groundwater discharging to the surface water. West had more groundwater flowing into the wetland cells than that of Gully, which helps to explain why it removes more overall N. With the flow budget into and out of the subsurface, the MODPATH simulates groundwater becoming surface wetland water (Table 6). Relating nitrogen (N) to the water molecules, “particles”, created shown by MODPATH, this simulation best shows how N would flow into and out of the wetland cells and how much is effectively removed before entering the Mackinaw River.

The provided model provides insight on the possible exchange of surface and groundwater to the highest possible degree. The incorporation of the clay liner in the model would have simulated a much slower connectivity and flow between the cells and groundwater. The model results indicate that the wetland cells serve as a sink for groundwater; this pattern would not change. However, the wetland cells receive more water from the groundwater without a clay liner. A K value more representative of glacial till and a model that included the clay liner would make it harder for water to enter or exit the wetland. With the inclusion of an impermeable layer, the overall patterns should not change, but the values of the exchange will decrease, potentially by 1 to 3 orders magnitudes because of the more restrictive clay unit. This would result in a change of dilution of the contaminated surface water as well as the residence time calculations for the surface water. If the liner had no leaks then there would be very limited connectivity. A decrease in the amount of groundwater discharging to the surface water would mean a lower input and a lower overall surface output from the wetland, which would effectively equate to an increased residence time. The clay liner would also reduce the amount of water entering the groundwater system, resulting in less nitrate reduction occurring in the subsurface. If the wetland was lined with a relatively impervious layer, the underlying strata would most likely be partially dry and leakage estimates would use equation 3 where A = wetland area, m^2; H_{lb} = elevation of the liner

$$Q_{gw} = K\ A\ [\frac{H_w - H_{lb}}{H_{lt} - H_{lb}}] \tag{3}$$

bottom, m; H_{lt} = elevation of the liner top, m; H_w = wetland water surface elevation, m; K = hydraulic conductivity of the liner, m/d; and Q_{gw} = infiltration rate, m^3/d (Kadlec & Wallace 2009). Having these variables included in a similar groundwater model would give a better idea of an estimated leakage and connectivity between the surface and groundwater.

CHAPTER V

CONCLUSION

Conclusions and Implications

The results of both the GFLOW and MODFLOW models agreed with topography, as there was a gentle overall gradient from North to South and groundwater flows into the natural sink of the Mackinaw River. There is no movement of particles from one wetland to the other and tile drains seem to have little to no effect on the groundwater flow at this local scale. Since the outflows from groundwater to the wetlands are significantly higher than the inflows from the surface water, it can be assumed that the wetlands have zones where they are being recharged from the subsurface. West had an average residence time of about 1.41 days (121,824 sec), which is much slower than Gully's 0.011 day (950 sec) (Table 1). With a greater overall groundwater recharge of 17.7 m^3/day into the West system verses the 13.8 m^3/day into the Gully system, it may help to explain why the larger wetland system removes more N due to additional groundwater helping to diffuse it and a longer surface residence time regardless of whether the K value changed. Gully however has a greater denitrification rate which could be due to different conditions in water or soil oxygen levels, or the fact that it retained more water than West, and was not fully explained by the groundwater model (Lindenbaum et al. 2010 and Table 1). As the nutrients can also travel within the groundwater, they have the potential of contaminating the water supply, but with a long enough distance, denitrification and the process of diffusion within the subsurface can also remove excess N. With the 10 years of travel time from West to the Mackinaw River and the six years it takes water to travel from Gully to Turkey Creek, any nutrients from West will have more time, both within the wetland system itself and the groundwater, to denitrify and more effectively remove nutrients before the water reaches surface features.

Recommendations for Future Research

This study focused on the regional groundwater flow parameters, but the water, and therefore nutrients, flowing within each individual wetland, in the surface water, have not quite yet been understood. The model domain was a local scale which included the two constructed wetlands, but since the scale was still quite large and focused on groundwater rather than the individual flow paths for the wetlands themselves only the interaction between surface and subsurface water. Future studies could take each wetland system separately, treating them as their own unit, to compare and contrast from not only each other, but for each of the three wetland cells they contain. The percentage of significance to the regional model would then be available to compare to the results of this more specified research. Using the basic structure of this groundwater model, another more specific model could be created to include an impermeable clay liner, which would involve a leak test at the demonstration site to determine if the liner performs as designed or is in fact leaky. Further still, a more comprehensive understanding of the snow melt, evapotranspiration, the two wetlands' anoxic conditions, and relating the areas of highest denitrification within each wetland to the groundwater discharging faces (into the wetland) could aid in abetting the question concerning why Gully has a greater denitrification rate than West.

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